Origins of the Kuroshio and Mindanao Current

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LONG-TERM GOALS

The boundary currents off the east coast of the Philippines are of critical importance to the general circulation of the Pacific Ocean. The westward flowing North Equatorial Current (NEC) runs into the Philippine coast and bifurcates into the northward Kuroshio and the southward Mindanao Current (MC). The partitioning of the flow into the Kuroshio and MC is an important observable. Quantifying these flows and understanding bifurcation dynamics are essential to improving predictions of regional circulation, and to characterizing property transports that ultimately affect Pacific climate. Fluctuations in the Kuroshio and MC can significantly impact variability downstream. For example, the Kuroshio penetrates through Luzon Strait into the South China Sea and onto the East China Sea shelf. The Kuroshio front dramatically alters stratification and may impact internal wave climate. This study incorporates observation, theory, and modeling to make fundamental advances in our knowledge of the origins of the Kuroshio and Mindanao current.

OBJECTIVES

The objectives of this program include quantifying flows and water properties, improving understanding of the dynamics of a bifurcation region, and establishing predictability of the three major currents in the region. The observational approach will have two major thrusts: (1) quantifying

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the fluxes of mass, heat, and salt in the NEC, Kuroshio, and MC, and (2) establishing Lagrangian patterns of flow. To quantify the seasonal cycle and to obtain an initial measure of interannual variability, these observations will be sustained over a three-year period. The bifurcation region is an interesting target, but the stagnation point of a turbulent flow is not an easy quantity to observe. The sustained observations will provide a test for models of the regions, and at the same time will be available for assimilation in models.

APPROACH

The proposed observing system employs a suite of complementary platforms to meet the challenges posed by this vast, highly variable study area. Guided by previous studies and by directed analysis of historical data, long-endurance autonomous gliders will be tasked to collect repeat occupations of key sections across the NEC, MC and Kuroshio. Because previous observational programs show that the Kuroshio sometimes reaches nearly to the coast, where glider operations can be difficult and risky, small arrays of moored instruments will augment glider sections to resolve the nearshore regions. Drifters and floats will be used to illuminate the pathways by which the NEC ultimately forms the Kuroshio and MC. Numerical efforts will aid interpretation and explore the predictive capabilities of regional models.

WORK COMPLETED

Gliders

Gliders are being used to observe the NEC and the Mindanao Current. Two Sprays are deployed from Palau every 4-5 months, one that proceeds northward across the NEC, and one that heads westward towards the MC. Operations commenced in June 2009 under a previous grant, and have continued uninterrupted. Turnarounds have occurred in September 2009, February 2010, and June 2010. The data set to date includes six crossings of the Mindanao Current, and eight sections across the NEC. The next turnaround is scheduled for November 2010.

Analyses so far are focusing on two issues: (1) flows in the NEC and Mindanao Current, and (2) submesoscale variability. Geostrophic currents through each section are calculated, referenced using the glider-observed depth-average velocity. The core of the Mindanao Current is found to be as strong as 1.5 m/s southward, with northward flows in the Mindanao Undercurrent approaching 1 m/s. The mean NEC is beginning to emerge from the collection of sections (Figure 1). Westward flow is confined mainly to the upper 500 m, and is strongest just north of Palau, where it peaks at about 0.5 m/s. Layers of high thermohaline variability are observed on isopycnals in the salinity maximum near 100 m, and in the salinity minimum near 400 m. The persistence of these layers will be a subject of continuing analysis

Drifters

The principal scientific objective of the Drifter Project is to map the near surface circulation that leads to the seasonal formation of the Kuroshio in the South Philippines Sea. This pattern is expected to be complex due to the existence of the Batan Islands and the Luzon Strait that direct flow into the South China Sea during the northeast Monsoon. The methodology is to enhance the historical data by deploying drifters from Korean merchant vessels that cross the Luzon Strait and the South Philippines Sea about every 35 days on a route from Kaohsiung, Taiwan to eastern Australia. The HYUNDAI Shipping Co picks up the drifters in Taiwan from Dr. Ruo-Shan Tseng Professor, Department of Marine Resources National Sun Yat-sen University

Ruo-Shan has worked with us before in the SCS on the ONR/NLIWI/DRI. His role is receive the drifters from a US manufacturer and to pack the drifters in water-soluble boxes for deployment from the fantail of container vessel 30' above the waterline, traveling at 30 knts. The deployments started in August 9, 2010 and are planned to last for 3 years. Two deployment cruises have been made with about 50% success rate. We have identified the problem as low power transmission from the drifters, now under repair.

The Philippines Seas were an active region for drifter deployments in August-September, 2010 due to the ONR Typhoon/DRI. These latter drifters appear in the region between the two cold eddies directly east of Taiwan. Figure 2 displays all drifter tracks on file for the August-September, 2010 period. It is apparent that typical Southwest monsoon conditions of the Kuroshio against Luzon are present during this time with no movements of drifters into the SCS. We are waiting for the dramatic change expected as the northeast Monsoon becomes fully developed by November.2010.

Modeling

Working with Xuebin Zhang, a Post-Doctoral researcher at SIO, we have performed MITgcm forward and adjoint modeling studies of the tropical Pacific Ocean, including the OKMC region. As an extension of Bo Qiu's work on the time-delayed wind influence on the OKMC bifurcation, we examined the sensitivity of boundary current transport and the sea surface height (SSH) in the region (12-14N, 127-130E) that Qiu identified as controlling the bifurcation (and transport). The model shows that sensitivity of SSH and transport to wind stress curl spreads to the east going backwards in time as suggested by the theory, but it also spreads in latitude, and shows considerable sensitivity to the equatorial waveguide. This is a generalization of standard Sverdrup transport or Island Rule theory, and includes time-dependence with realistic advection and wave propagation without making the long-wave approximation. The results are being written up for publication now.

Ocean model output for the region of interest was extracted from three global simulations: stand-alone global 0.1° Parallel Ocean Program (POP) and 1/12° Hybrid Coordinate Ocean Model (HYCOM), and a new fine resolution fully-coupled Community Climate System Model (CCSM) global simulation configured with a 0.25°atmosphere and a 0.1° ocean (http://www-pcmdi.llnl.gov/uhrccs/) that has been run for 2 decades. The stand-alone models were forced with synoptic atmospheric fluxes. In the case of POP full-depth daily averages of the state variables, Ertel potential vorticity, and all momentum, heat, and salt fluxes were available in the OKMC region for 1999-2001. The HYCOM output consists of full-depth daily state variables from forward and data assimilative simulations for overlapping years since 2003. Jessie Carman (military faculty, USNA) spent two weeks at SIO over the summer of 2010 collaborating with us to become familiar with the details of the simulations. Regional model fidelity analyses were started. Barotropic streamfunction calculations from monthly global POP fields are underway allowing us to measure the seasonal migration of the bifurcation latitude as well as calculate the partitioning of flow into the Mindanao and Kuroshio Currents. Spontaneously-forming Category 4 typhoon events have been identified in CCSM in the tropical northwest Pacific. Six-hourly full-depth ocean output has been archived for a two-month period during the typhoon season. This output is being analyzed to understand the impact of this extreme weather event on the region of interest.

RESULTS

With OKMC started less than one year ago, the most signficant results lay in the future. At this stage, the following results are most evident.

- Strong stirring is evident in the salinity extrema. This feature is consistent with the relatively young age of the water in the extrema relative to the inflection level between.
- The mean NEC is becoming clearer, with the strongest flows in the south and near the surface.
- SSH in the region is found to be sensitive to wind stress curl throughout the basin to the east, with special sensitivity in the equatorial waveguide.

IMPACT/APPLICATIONS

- The demonstration of glider utility in a strong western boundary current should influence future glider operations in similarly strong flows. Gliders are showing potential for the sustained observation of major ocean currents.
- The value of drifters for regional oceanography is being further established through this program.
- Quantifying the predictability of currents using basin-wide wind stress curl is helping to set bounds for the fidelity of ocean models.

RELATED PROJECTS

This project takes advantage of glider technology that has been developed through grants from several agencies including ONR, NSF, and NOAA.

PUBLICATIONS

Cole, S. T., D. L. Rudnick, and J. A. Colosi, 2010: Seasonal evolution of upper-ocean horizontal structure and the remnant mixed layer. *Journal of Geophysical Research*, **115,** C04012, doi:10.1029/2009JC005654.

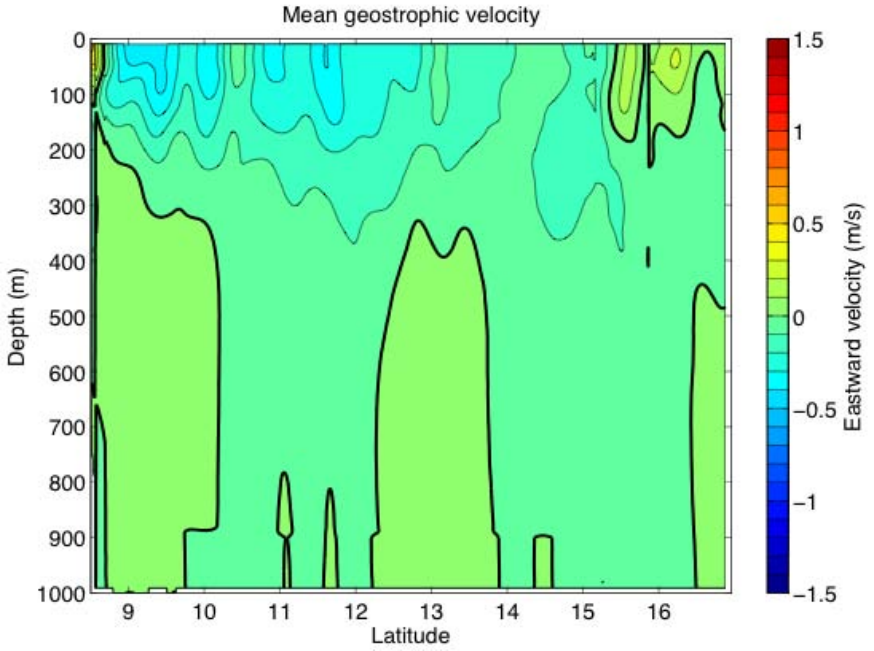

Figure 1. Mean geostrophic velocity in the NEC along about 134°20'N. Westward flow is strongest shallow in the southern part of the section (just north of Palau).

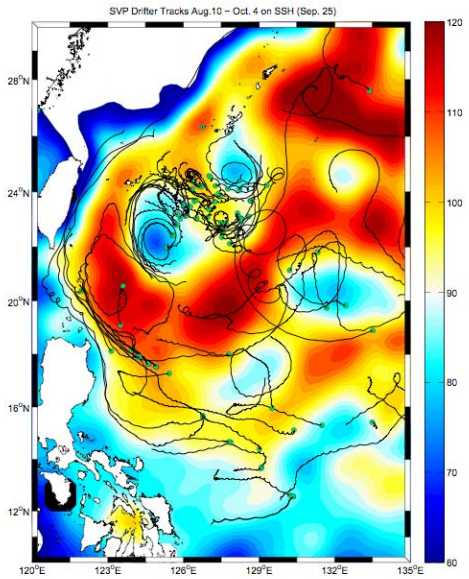

Figure 2. SVP-Drifter tracks in the Philippines Seas from August 10 to September 20. 2010, overlain on the AVISO anomaly on Maximenko and Niiler mean sea level the same period.